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Multiple impact event in the paleozoic: Collision with a string of comets or asteroids?

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Abstract. Eight circular geologic structures ranging from ~3 to 17 km in diameter, showing evidence of outward-directed radial deformation and intensive brecciation, lie within a linear swath ~15 km wide along a straight line stretching ~700 km across the United States from southern Illinois through Missouri to eastern Kansas. Based on their similar geological characteristics and the presence of diagnostic and/or probable evidence of shock, these structures, once classified as 'cryptovolcanic' or 'cryptoexplosion' structures, are more confidently ascribed to hypervelocity impact. No other similar occurrence of aligned features is known, and we calculate the probability of a chance alignment to be $<10^{-9}$. The unusual alignment suggests that the features are coeval and related to a multiple impact event, with a best-constrained late Mississippian-early Pennsylvanian (~330-310 Myr) age. Calculations suggest that the proposed impact-crater chain is unlikely to have been formed by an incoming impactor disrupted by terrestrial or lunar tidal effects, and may have been the result of a string of asteroidal or cometary objects produced by breakup within the inner Solar System.

Introduction

The spectacular recent impact of Comet Shoemaker-Levy 9 on Jupiter has stimulated much interest in the record of comet or asteroid breakup leading to multiple impacts on the planets. Crater chains from multiple impacts are known to exist on the jovian satellites [*Melosh and Schenk*, 1993], and *Melosh and Whittaker* [1994] have recently identified chains of closely spaced craters on the Moon. Although a number of double craters occur on the Earth [*Melosh and Stansberry*, 1991], no long multiple impact crater chains have been recognized.

There is, however, at least one line of features on the Earth that is worth reconsidering as a possible chain of impact structures that might have resulted from the collision of a train of comets or asteroids. *Snyder and Gerdemann* [1965] described eight peculiar, circular geologic features along a straight line stretching ~700 km across the United States from southern Illinois to eastern Kansas (from east to west, Hicks Dome, Avon, Furnace Creek, Crooked Creek, Hazel Green, Decaturville, Weableau, and Rose Dome) (Fig. 1, Table 1); other similar features, yet to be recognized, may lie along the same trend [*Snyder et al.*, 1965]. These features show evidence of radial deformation and intense brecciation, and lack typical volcanic rocks. Two of the structures, Decaturville and Crooked Creek, are now classified as proven impact structures based on the discovery of features diagnostic of shock (shatter cones and shocked quartz) [*Grieve and Shoemaker*, 1994].

Here, we provide evidence that the geologic similarity of the structures, their unusual alignment, most likely ages, and the discovery of definite and probable shock features at several of the sites support the idea that the structures are coeval and related to a multiple impact event, possibly from a train of asteroidal or cometary objects from a parent body that broke up in the inner Solar System.

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The Illinois-Missouri-Kansas Structures

The early 'cryptoexplosion' model. The eight structures of the Illinois-Missouri-Kansas line display similar evidence for intense geological deformation and brecciation, and were originally classified as 'cryptovolcanic' structures (circular features marked by radial symmetry, central uplift and encircling, outward-directed folds, radial and concentric faulting, and intense brecciation), a term first used by *Branca and Fraas* [1905] for the Steinheim Basin in Germany. By 1936, *Bucher* could list six structures in the United States, including the Decaturville structure, with characteristics (including shatter cones) that closely corresponded to those of Steinheim. The term 'cryptovolcanic' was later changed to 'cryptoexplosion' by *Bucher* [1963], who defined these structures as being produced by a process involving explosive "release of gases under high tension, without the extrusion of any magmatic material, at points where there had previously been no volcanic activity".

Boon and Albritton [1936, 1938] argued for an impact origin for these features, and *Dietz* later [1963] pointed to the discovery of shatter cones and minerals such as coesite, considered diagnostic of impact shock, at a number of typical 'cryptoexplosion' sites. In the last few decades, careful study

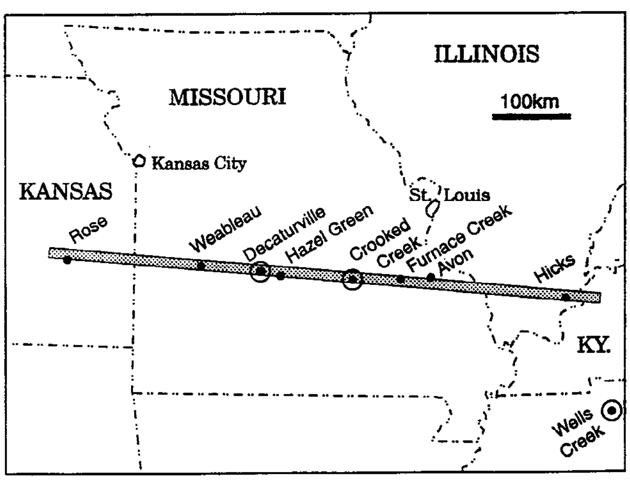

Figure 1. Chain of known and probable impact structures in Kansas, Missouri, and Illinois [*Snyder and Gerdemann*, 1965]. Only one other similar structure is known within the map area, the Wells Creek impact structure (12 km diameter, 200±100 Myr) in northwest Tennessee (shown). Width of shaded swath = 15 km. Circled structures are listed as proven impact craters in the latest crater list [*Grieve and Shoemaker*, 1994].

Table 1. Proposed Terrestrial Impact Crater Chain

Structure	Diameter (km)	Projectile Diam.† (km)	Estimated or Tentative (?) Age Assignment	Evidence of Impact Shock (*diagnostic)
Rose Dome	>3	>0.1	post-Penn. <300Myr (?)	Precambrian granite with shattered quartz grains, matrix possibly recrystallized glass [*Twenhofel*, 1926]; glassy dikes (cf. pseudotachylite*) [*Knight and Landes*, 1932]
Weableau	5	0.2	**Late Miss.-Early Penn. (~330-310 Myr)**	Breccia dikes [*Snyder and Gerdemann*, 1965]
Decaturville	6	0.3	<300 Myr	Shatter cones*, breccia dikes [*Snyder and Gerdemann*, 1965; *Offield and Pohn*, 1977]
Hazel Green	?	?	Late Camb. ~500 Myr (?)	Shattered quartz grains [*Snyder and Gerdemann*, 1965]
Crooked Creek	7	0.3	**320±80 Myr**	Shatter cones*, breccia dikes, shattered quartz [*Snyder and Gerdemann*, 1965]; shocked quartz* [*Kiilsgaard et al.*, 1962]
Furnace Creek	≤15?	<0.8	Late Camb. ~500 Myr (?)	Shattered quartz grains, spherulites [*Snyder and Gerdemann*, 1965]
Avon	17	0.9	post-Devonian <360 Myr	Possible devitrified melt glass with spherulitic structure, highly shattered granite inclusions, breccia dikes [*Tarr and Keller*, 1933; *Rust*, 1937]
Hicks Dome	16	0.9	**Late Miss.-Early Penn. (~330-310 Myr)**	"quartz with numerous lines of tiny inclusions and showing prominent undulatory extinction" (cf. shocked quartz*) [*Weller and Grogan*, 1945]; shattered quartz grains, breccia dikes [*Weller et al.*, 1952; *Brown et al.*, 1953].

†Projectile diameter derived from formulae in *Shoemaker et al.* [1990]
Best-constrained ages from geological information in bold-face type (for refs. see text).

of many 'cryptoexplosion' structures has produced diagnostic evidence of shock, establishing their origin by hypervelocity impact [e.g., *McCall*, 1979; *French*, 1990].

Of the 71 structures listed in *McCall* [1979] as 'cryptoexplosion' or possible impact structures (his Class IV), 57 are now listed as proven impact structures [*Grieve and Shoemaker*, 1994], and most of the others have not been restudied for evidence of shock metamorphism. None of the 'cryptoexplosion' structures have been established as of non-impact origin. In fact, the type example of a 'cryptoexplosion' structure, the Steinheim Basin [*Bucher*, 1936], and the syntype for the U.S., the Wells Creek structure [*Dietz*, 1963], are now recognized as typical impact structures. Thus, the process of 'cryptoexplosion' remains unknown, with no verified examples, and almost all workers now consider the term and the process it supposedly describes as defunct [e.g., *Dence*, 1972; *Grieve and Robertson*, 1979; *French*, 1990].

Evidence of hypervelocity impact. Several lines of evidence support the interpretation of the chain of features as impact structures. The Decaturville and Crooked Creek structures have been found to show diagnostic evidence of shock (shatter cones and shocked quartz) [*Kiilsgaard et al.*, 1962; *Offield and Pohn*, 1977] , and are now listed as proven impact craters [*Grieve and Shoemaker*, 1994]. We have reviewed the geological literature for all eight structures, and have identified in these detailed early descriptions additional evidence for shock deformation in the form of quartz with planar features, highly shattered quartz, probable devitrified melt glasses with typical spherulitic structures, and intrusive (non-igneous) breccia dikes of various kinds [see *French and Short*, 1968] (Table 1).

The eight aligned features occur within a linear swath ~700 km long and ~15 km wide (Fig. 1). Given the sparse distribution of other similar features in the central U.S. region, [*McCall*, 1979; *Grieve and Shoemaker*, 1994], we estimated the probability of a chance alignment in the following way. Using the Decaturville and Crooked Creek impact structures to define a line, the probability of the next structure falling along this line of length D, in a zone of width w, as opposed to anywhere in a circle of diameter D, is $Dw/[\pi (1/2D)^2] = 1.27w/D$.

For our case, where D = 700 km and w = 15 km, the probability for 6 subsequent structures is $(1.27w/D)^6$ or only $\sim 4 \times 10^{-10}$, indicating that the alignment of these structures is very unlikely to have been accidental. We note that if the swath is extended toward the east another ~420 km, it passes very close to the Middlesboro impact structure (6 km in diameter, estimated age <300 Myr) in eastern Kentucky [*Grieve and Shoemaker*, 1994].

We have also summarized all available information as to the geologic ages of the structures (Table 1). Because of a lack of detailed study, the ages of some of the structures are known only tentatively [*Snyder and Gerdemann*, 1965; *McCall*, 1979; *Grieve and Shoemaker*, 1994]. The best-constrained geological ages (for those structures with radiometric age determinations, or overlying undeformed strata in close succession to those deformed) (Table 1), however, are consistent with a possible late Mississippian or early Pennsylvanian (~330-310 Myr) multiple impact event, which would put the location close to the paleoequator. *Orth et al.* [1986] found enhanced iridium (up to 0.38 ppb) near the Mississippian/Pennsylvanian (mid-Carboniferous) boundary in Oklahoma and Texas, which is characterized by increased rates of marine extinction [*Sepkoski*, 1993].

Formation of the Proposed Crater Chain

Breakup by terrestrial or lunar tidal forces. If the structures resulted from the breakup of a single body, then the diameters of the inferred impactors, based on crater scaling laws [*Shoemaker et al.*, 1990], suggest a parent body several km in diameter. The maximum separation of incoming objects that break up within the Earth's Roche limit is estimated by $a_0 \exp(v_{esc}/v_{imp})$, where v_{esc} is the Earth's escape velocity,

v_{imp} is the relative impact velocity, and a_0 is the initial diameter of the parent object [after *Melosh and Stansberry*, 1991]. For typical impact velocities and angles, this would produce craters separated by <10 km, much less than the average ~100 km spacing of the terrestrial structures (Fig. 1). Greater spacing could be produced at very low impact angles (grazing incidence), although this would be a rather unlikely occurrence.

Lunar crater chains have been attributed to comets disrupted by the Earth's tidal forces [*Melosh and Whittaker*, 1994]. As a second possibility, we considered the converse situation: a body disrupted by close pass of the Moon that subsequently impacts the Earth. Assuming impactors of similar density, the ratio of the Moon's Roche limit to that of the Earth is $R_m/R_e = (r_m/r_e)(\rho_m/\rho_e)^{1/3}$, where r and ρ are the radius and density of each body. Therefore, the flux of impactors disrupted by the Moon is substantially less than that disrupted by the Earth, proportional to the areas defined by the limits as radii, or $(R_m/R_e)^2$. This difference is compensated, however, by the greater area for subsequent interception presented by the Earth as compared to the Moon, $\propto (r_e/r_m)^2$.

Thus, the ratio of the number of comets disrupted by the Moon and striking the Earth to those disrupted by the Earth and striking the Moon may be approximately $(\rho_m/\rho_e)^{2/3} = 0.7$. Based on the lunar record, this would mean only about one such terrestrial cratering event in the last 4 Byr. An exception, however, would be the case of a relatively slow approach velocity (v_{inf} ~1 km/sec), where the Earth's gravitational focusing factor $(1+v_{esc}^2/v_{inf}^2)$ becomes large, and this coupled with the smaller Earth-Moon distance in the Late Paleozoic would increase the probability of observing such a crater chain. Furthermore, calculations suggest that such a slow moving 1 km diameter comet passing close to the Moon would spread into a fragment chain ≥700 km long (*H.J. Melosh*, pers. comm.). The problem with this scenario is that such a small approach velocity is also an unlikely occurrence [*Bottke et al.*, 1994].

Bodies in orbit around the Earth? The chain of E-W impact structures stretching across the central U.S. is reminiscent of the trail of impact sites in the jovian atmosphere created by the succession of impacts of Shoemaker-Levy 9 on rapidly rotating Jupiter. The Jupiter impact sites were produced by the long (~2x10^6 km) orbiting string of comets during several revolutions of the planet. Capture of asteroids or comets by the Earth is considered unlikely due to the narrowness of the required entry window, hence it seems improbable that the strafing of impactors that formed the terrestrial crater chain came from bodies that were orbiting the planet. Recently, however, *Shaw* [1994] suggested that non-linear resonance effects in the inner Solar System might make capture into Earth orbit, and subsequent breakup, more probable. Although this hypothesis remains speculative, we note that the near-equatorial paleolocation of the proposed crater chain might be expected from impacts of fragmented objects that formed a planetary ring.

Breakup in the inner Solar System. A third possibility for the origin of the crater chain is the breakup of a comet in the inner Solar System. Comets (and perhaps some asteroids) are apparently rather fragile objects [*Asphaug and Benz*, 1994], and observations suggest high rates of cometary splitting in the inner Solar System [*Weissman*, 1980; *Chen and Jewitt*, 1994]. The apparent crater-size distribution, with the largest objects at the eastern end of the chain, might be taken to favor a randomly split, rather than a tidally disrupted, parent body (*P. Weissman*, pers. comm.). This also raises the question of whether such fragile impactors with diameters of 200-300 m would have survived passage through the atmosphere to create the impact structures [*Chyba et al.*, 1993], making asteroidal impactors perhaps more likely.

If the bodies were in heliocentric orbit, then the Earth would have been moving through their path at the planet's orbital velocity of 29.8 km/s. Therefore, given the ~100 km spacing of the craters, the impacts would have been only 3-4 seconds apart, and with typical encounter velocities (15 to 60 km/s) the separation of the incoming bodies could have been only ~45 to 240 km, with the length of the eight-fragment string ranging up to ~1,700 km. (The discovery of additional impact sites beyond the known crater chain would indicate a longer impactor train.)

Split comets are observed to move away from one another at velocities of a few m/s (*Weissman*, 1980; *Sekanina*, 1982). Assuming a separation velocity of 3 m/s, the breakup event could have occurred from ~4 to 22 hours prior to Earth impact. At velocities of 15 to 60 km/s, this could have been from 2x10^5 to 5x10^6 km from the Earth.

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